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## **Abstract**

To test a central assumption of the increased perceptual capacity account in individuals with Autism Spectrum Disorder (ASD), the effects of perceptual load and target-stimulus degradation on auditory detection sensitivity were contrasted. 14 adolescents with ASD and 16 neurotypical controls performed a visual letter search task under three conditions: low perceptual load, high perceptual load and low perceptual load with a degraded target while simultaneously detecting an auditory tone in noise. For both participants with ASD and neurotypical controls, increasing perceptual load and target degradation increased task difficulty as indexed by reaction times and accuracy. However, only increasing perceptual load reduced subsequent auditory detection sensitivity. The study confirms that perceptual load, and not task difficulty, modulates selective attention in ASD.

**Keywords:** Autism Spectrum Disorder, auditory detection sensitivity, selective attention, perceptual load, task difficulty

Autism spectrum disorder (ASD) is characterized by primary impairments in social interaction and communication, and the presence of restrictive and repetitive behaviors and interests (DSM-5, American Psychiatric Association 2013). Alongside these core impairments, attentional atypicalities often manifest that are pervasive (Keehn et al. 2012) and emerge early in life (Osterling and Dawson 1994; Swettenham et al. 1998; Gliga et al. 2014). Prospective studies of infants at high familial risk for ASD have documented atypical functioning across a range of aspects of attention (Gliga et al. 2014), and these atypicalities could potentially serve as a biomarker to identify biologically and clinically meaningful ASD subgroups (Pierce et al. 2016). Further, differences in perceptual processing have consistently been reported in individuals with ASD that may confer advantages on a range of tasks including visual search tasks (O'Riordan 2004; O'Riordan et al. 2001; Plaisted et al. 1998; Joseph et al. 2009) and embedded figures tasks (Shah and Frith 1993; Jolliffe and Baron-Cohen 1997), and in the auditory modality by higher incidence of perfect pitch (Heaton 2003) and enhanced frequency discrimination (Bonnell et al. 2010; Jones et al. 2009). Alterations in attentional and perceptual processing have potentially important developmental consequences by changing the child's experience of the environment and further restricting opportunities for social learning. Across development, these processes may then interact in a complex fashion with other processes at multiple levels (e.g. genetic, biological, neural, cognitive) to contribute to the clinical phenotype that characterizes ASD (Johnson 2011). Understanding the attentional mechanisms in individuals with ASD may therefore help explain the atypical trajectories of attentional development in ASD and further clarify how these atypicalities may contribute to the manifestation of the core symptoms of the condition.

Attempting to account for attentional atypicalities in ASD, an emerging theory suggests that ASD may be associated with an increased perceptual capacity (Remington et al. 2009; Remington et al. 2012). This theory follows from the application of perceptual load theory

(Lavie 1995) and its limited-capacity approach to selective attention and perception. According to perceptual load theory, the extent to which distracting stimuli are processed depends on the perceptual load of a task (e.g. number of task-relevant items, or subtlety of a discrimination). A task involving a high perceptual load is likely to exhaust an individual's capacity, leaving no additional resources to process task-irrelevant information. By contrast, a task with low perceptual load does not exhaust full capacity, resulting in automatic spill-over of remaining attentional resources to the processing of task-irrelevant information until overall capacity is reached. While there have been conceptual and methodological challenges to load theory (see Benoni and Tsal 2012; Giesbrecht et al. 2014; Murphy et al. 2016 for reviews), the large amount of research supporting the theory converging on similar evidence across different experimental paradigms and data modalities suggests that load theory constitutes a useful paradigm to test the implications for selective attention in clinical populations.

The proposal that individuals with ASD may have an increased perceptual capacity arose from the observation that on some tasks individuals with ASD demonstrate superior performance (e.g. visual search and embedded figures tasks; Shah and Frith 1993; O'Riordan et al. 2001; O'Riordan 2004; Hessels et al. 2014), while on others they show a heightened vulnerability to distraction (Burack 1994; Christ et al. 2007; Adams and Jarrold 2012). This pattern of performance in ASD could be predicted if individuals with ASD had a higher perceptual capacity than neurotypical (NT) participants. Since according to load theory all stimuli are processed automatically until perceptual capacity is reached, individuals with a high perceptual capacity should show indiscriminate processing of more information than those with a lower capacity. This would lead to superior performance on tasks where all the information is task-relevant, as is seen for individuals with ASD in visual search tasks and embedded figures tasks, particularly when perceptual load is high (e.g. when array sizes are large in visual

search), but also increased distractor processing when this information is task-irrelevant (Burack 1994; Christ et al. 2007; Remington et al. 2009; Adams and Jarrold 2012).

A number of studies using a range of task paradigms have now found evidence for an increased perceptual capacity in individuals with ASD relative to NT individuals (Remington et al. 2009; Remington et al. 2012; Swettenham et al. 2014; Tillmann et al. 2015; Tillmann and Swettenham 2017). For example, enhanced processing of extraneous information in ASD under conditions of high perceptual load has been shown for visual distractor processing (Remington et al. 2009), visual detection sensitivity (Remington et al. 2012), detection of an unexpected task-irrelevant visual stimulus in an inattention blindness task (Swettenham et al. 2014) and more recently for auditory stimuli presented in a cross-modal context (Tillmann et al. 2015; Tillmann and Swettenham 2017).

A problematic issue across these studies, however, is that an increase in perceptual load also typically involves an increase in task difficulty and associated slowing of overall reaction times (RTs) and increase in error rates. For example, in studies that manipulated perceptual load via search set size (i.e. 1, 2, 4 or 6; Remington et al. 2009; Remington et al. 2012; Tillmann and Swettenham 2017), RTs typically increase by about 4-15% for each incremental load increase (e.g. comparing set size 2 vs. set size 4) and increase by up to 28% comparing the lowest perceptual load (set size 1) to the highest perceptual load condition (set size 6). This effect is robust, with small to moderate effect sizes when comparing adjacent load conditions (range of Cohen's  $d$ : [0.44 – 0.84]) and large effect sizes comparing the lowest- to the highest load condition (range of Cohen's  $d$ : [1.34 – 1.56]). Error rates also follow this pattern, with an increase in error rates between adjacent load conditions of 2% - 29% (range of Cohen's  $d$ : [0.03 – 1.8]) and of 40% between lowest-and highest load conditions (range of Cohen's  $d$ : [0.67 – 3.86]). Thus, the differential effect of higher perceptual load on attention in individuals with

ASD might be attributed to general task difficulty rather than load-specific effects on perceptual resources.

In an important extension to load theory involving neurotypical adults, Lavie and de Fockert (2003) attempted to separate the effects of perceptual load from the general effects of task difficulty on attention. The perceptual load of a task is operationally defined as either (i) an increase in the number of relevant items/units in a display for the same task, or (ii) an increase in the complexity of perceptual operations/perceptual processing requirements involved in the relevant task for the same number of items (Lavie 1995). Attentional capacity is therefore consumed by the additional processing of these items or by imposing additional and/or more complex perceptual processing requirements. Task difficulty, however, can be achieved by degrading the sensory quality of a target item (e.g. by reducing the contrast or size of a target). Lavie and de Fockert (2003) proposed that whilst manipulations of both perceptual load and target stimulus degradation will result in increased task difficulty, degrading the sensory quality of a target item should make discrimination more difficult (i.e. making identification subject to sensory ‘data limits’) without putting any further demand on attentional ‘resource limits’ (Norman and Bobrow 1975). They hypothesized that the extent to which distractors will be processed depends critically on the type of manipulation of task difficulty: increasing task difficulty by increasing perceptual load will lead to reduced distractor processing, whereas increasing task difficulty by degrading the target stimulus will not reduce distractor processing. To test this hypothesis, they presented neurotypical adults with a variation of the Eriksen response-competition task (Eriksen and Eriksen 1974) that required identification of a relevant target letter within a central search array (either X or N) while attempting to ignore a distracting letter in the periphery. This distractor could be either compatible (an X if target was X) or incompatible with the target response (an X distractor when the target was N, or vice versa). The perceptual load of the task was varied by increasing

the number of non-target letters in the central search array to create a low perceptual load condition (only target letter present) or high perceptual load condition (target letter and seven neutral non-target letters). Participants also performed a condition of low perceptual load with a degraded target letter. In this condition, only the target letter was presented in the central search array (i.e. constituting a low perceptual load display), yet the size and contrast of the target letter were reduced relative to the other conditions, thereby degrading the sensory input. The results indicated that both increasing perceptual load and stimulus degradation resulted in an increase in task difficulty as indexed by longer RTs and higher error rates compared to a low perceptual load condition that featured an intact target letter. However, whereas an increase in perceptual load resulted in reduced distractor processing, an increase in target degradation had no effect on distractor processing. Similar effects were also observed when the presentation time of the target was decreased, when the target was followed by a mask, or when the eccentricity of the target was increased to reduce retinal acuity. This pattern of results suggests that increasing task difficulty (via stimulus degradation) without increasing the perceptual load of the task is not sufficient to reduce distractor interference. Instead, distractor processing critically depends on the level of perceptual load in the relevant task and available attentional resources (Lavie and de Fockert 2003).

These preliminary findings were recently further validated by Yeshurun and Marciano (2013) who contrasted the effects of sensory degradation and perceptual load on target response competition by degrading either only the target stimulus or distractor or both the target and distractor stimulus. In line with Lavie & deFockert (2003) they found that low load with target degradation and high load no target degradation led to a deterioration of task performance relative to a baseline low load condition without degrading the target letter. Importantly however, while distractors were processed across all low load conditions regardless of stimulus

degradation, distractor interference was only significantly reduced at high perceptual load levels.

In the current study, we wanted to examine whether the differential effect of load and stimulus degradation on selective attention is also observed for participants with ASD, particularly since the previous studies examining the effect of perceptual load on selective attention in ASD do not clearly separate the effects of perceptual load from the effects of task difficulty. To do so, we adopted a dual-task paradigm by Tillmann and Swettenham (2017). In this study, participants had to perform a visual search task (i.e. identify X or N) at varying levels of perceptual load and detect the presence/absence of a critical auditory stimulus presented simultaneously to the visual search display. Tillmann & Swettenham (2017) demonstrated that when visual perceptual load was low (i.e. only the target letter was presented in the search display), detection sensitivity for the auditory stimulus was similarly high for TD individuals and individuals with ASD. At a higher level of perceptual load (i.e. target letter + 3 additional non-target letters), detection sensitivity was reduced for the NT group but not the ASD group. At the highest load condition (i.e. target letter + 5 additional non-target letters), designed to exhaust capacity in all individuals, both groups demonstrated similarly reduced auditory detection performance. This suggests that individuals with ASD required higher levels of perceptual load than NT individuals before detection sensitivity was affected by the perceptual load of the task.

The decision to adopt this task paradigm rather than the Erikson response-competition task used by Lavie and de Fockert (2003) was driven by several methodological concerns. The latter task uses an indirect and less than optimal measure of attention by assessing response interference effects, i.e. RT costs associated with the presence of a response-incongruent distractor (requiring the opposite target response). Yet, longer reaction times incurred on incompatible versus compatible trials may not necessarily reflect distractor perception but



could rather relate to post-perceptual processes such as response selection. Alternatively, distractors may never enter awareness regardless of load, but activate more strongly unconscious recognition processes of distractor-/target-response associations under low perceptual load. The effects of reaction times can therefore potentially be attributed to a range of mechanisms and cannot provide clear evidence whether distractors were actually consciously perceived and thus entered awareness. Thus, whether the reported effects also translate to a more robust measure of attentional capture (measuring detection sensitivity) and to attentional functioning across sensory modalities, remains unknown. For these reasons, we further investigated the effects of perceptual load and stimulus degradation within a cross-modal dual-task paradigm in individuals with ASD and a neurotypical control group. Participants were required to perform an adaptation of the dual-task paradigm used by Tillmann and Swettenham (2017), consisting of a central letter search task and an auditory detection task. Three conditions of interest were created: a low perceptual load condition (target letter presented alone), a high perceptual load condition (target letter and five additional neutral letters), and a low perceptual load with a degraded target letter condition. It was predicted that in line with previous findings on neurotypical adults (Lavie and de Fockert 2003), increasing both perceptual load and sensory degradation would result in increased RTs and error rates. However, only an increase in perceptual load would reduce detection sensitivity, whereas manipulating sensory degradation would have no effect on detection sensitivity. We predicted that this pattern would be similar in both groups.

## Method

### *Participants*

18 adolescents with ASD and 19 NT adolescents participated in this study ( $M_{\text{Age}} = 14\text{y } 8\text{m}$ ,  $SD_{\text{Age}} = 9\text{m}$ ). Informed consent was obtained from all individual participants included in

the study. All participants with ASD had a clinical diagnosis of ASD according to DSM-IV (American Psychiatric Association 1994). In addition, parent-reported ASD symptomatology was measured using the *Social Communication Questionnaire* (SCQ, Rutter et al. 2003). Exclusion criteria included target-letter accuracy rates of less than 50% for any set size manipulation on the letter search task and detection accuracy of the auditory stimulus of less than 30% in any experimental condition. The lower cut-off value for detection accuracy compared to target-letter accuracy was chosen to capture more variability in detection performance as a function of perceptual load conditions, while the higher value for accuracy rates was used to exclude any participant with chance-level performance on the visual task. Following these exclusion criteria, 4 participants with ASD and 3 NT participants were removed prior to the analysis. The remaining 16 NT (11 males, 5 females) and 14 participants with ASD (11 males, 3 females) were matched for non-verbal ability using the *Raven's Standard Progressive Matrices* (Raven et al. 1998) and chronological age (see Table 1 **Error! Reference source not found.** for descriptive statistics). Independent samples t-tests indicated that there were no significant differences between groups on any of these measures (maximum  $t$ -value = 1.534, minimum  $p$ -value = .136). The size of the sample studied is in line with previous studies using a similar experimental design (Remington et al. 2009; Remington et al. 2012; Tillmann and Swettenham 2017).

--Table 1 about here--

#### *Apparatus and stimuli*

Visual stimuli were created with Microsoft Visual Basic and presented on an IBM Lenovo Thinkpad 14.1" at a viewing distance of 60cm. A dual-task paradigm based on Tillmann and Swettenham (2017) was employed that required participants to identify a target letter in a central search array and then indicate presence or absence of an auditory stimuli embedded in noise. Each display consisted of a target letter ('X' or 'N') that was presented

randomly and equiprobably in one of six possible positions around the circumference of a circle centered at fixation ( $1.7^\circ$  visual angles). In the low perceptual load and degraded low perceptual load condition, the other positions were occupied by perceptually non-similar small letter *O*s ( $0.2^\circ \times 0.2^\circ$  visual angles). In contrast, in the high perceptual load condition, perceptually similar non-target letters (H, K, V, Y and Z;  $0.6^\circ \times 0.6^\circ$  visual angles) occupied the other positions that served to load the search for the target stimulus. Each non-target letter appeared equally often and presentation across possible positions was randomized. Target-stimulus degradation in the degraded low load condition relative to the other two perceptual conditions was achieved by reducing the size ( $0.2^\circ \times 0.2^\circ$  vs.  $0.6^\circ \times 0.6^\circ$ ) and intensity (RGB 65, 65, 65 vs. RGB: 255, 255, 255) of the target stimulus (see Figure 1 for an illustration). A similar manipulation has previously been shown to induce ‘data limits’, without inducing ‘resource limits’ (Lavie and de Fockert 2003).

-- Figure 1 about here --

All auditory stimuli were prepared with Audition and Speech Filing System 4/Windows (University College London) and calibrated prior to the experiment by a Bruel & Kjaer 4153 artificial ear and Ono Sokki CF-350Z spectrum analyzer. Simultaneously with the onset of the visual task, a speech-shaped noise masker (48db sound pressure level) was played continuously for two seconds through a pair of Sennheiser HD 25-1-II stereo headphones. The critical stimulus, a saw-tooth wave (frequency range of 85-150Hz) was played together with the noise masker on 50% of all trials and co-occurred with the onset of the visual central search array and was matched in duration with the visual presentation of the central letter search task (i.e. 176ms). Presentation of (a) the target sound and noise or (b) noise-only stimulus was randomized across trials.

Before starting the main experiment, perceptual thresholds for the critical stimulus in noise were established for each participant individually using a two alternative forced-choice

(2AFC) adaptive threshold procedure. Perceptual thresholds were estimated by identifying the signal-to-noise ratio (SNR) at which each participant was just able to identify the critical stimulus in noise. A larger SNR reflects easier-to-perceive auditory targets in noise and may be taken as an index of decreased/poor ability to discriminate the auditory target sound from the background noise.

The adaptive threshold procedure was composed of two stimuli presented consecutively: the target sound embedded in noise and a noise-only stimulus. Order of presentation of stimuli was randomized across trials. After presentation, participants were required to indicate which stimuli was the target sound-in-noise. Correctly discriminating the critical stimulus in two consecutive trials resulted in a reduction in the signal-to-noise ratio (SNR) by -0.5db in the subsequent third trial (i.e. making it more difficult to discriminate the target sound-in-noise), while a single incorrect response resulted in an increase in the SNR by +0.5db in the next trial (i.e. facilitating discrimination). Since two consecutive correct responses are required for a decrement but a single incorrect response leads to an increment (2-down, 1-up), the percent-correct point targeted by the staircase is at the 70.7% mark. Individual thresholds were based on an average of five reversals (point at which direction is changed, i.e. either when producing a correct answer followed by an incorrect answer or when producing two correct answers after an incorrect answer).

Based on each individual's threshold level, a five unit increase in the SNR (i.e. +2.5db, making it easier to detect the target sound in noise) was applied to the target sound in-noise stimulus used in the main task. This adjustment served two purposes. First, the SNR stimulus fell well above the threshold to make it easily detectable in the main task yet was calibrated to each individual's threshold to take into account any individual differences in perceptual thresholds. And second, since the adjustment was constant across participants, this kept the absolute difference between signal (target sound) and signal-to-noise threshold level equivalent across

participants. Upon starting the main experiment, the adjusted SNR stimulus was played to each participant and they were asked if they can easily detect the sound-in-noise. Failure to detect the sound resulted in repeating the thresholding procedure. There were no group differences between the ASD and the TD group in SNR thresholds.

### *Procedure*

Each trial featured a fixation cross (presented for 1000ms), the visual search array (176ms) and then a blank screen probing for a response to the visual input (i.e. 'X' or 'N' present). Participants were instructed to indicate as quickly but also as accurately as they can via an appropriate keypress (keypress of 'X' or 'N' for X and N respectively). Immediately following this response, a white question mark (measuring  $0.6^\circ \times 0.6^\circ$  visual angles) was presented at fixation and participants had to indicate whether the target auditory stimulus was present or absent (see Figure 2 for an example trial). Participants always needed to first make the visual judgment ('X' or 'N') and then indicate via a separate keypress whether the sound in noise was present (press 'S') or absent (only noise; press 'A'). A blank screen was then displayed for 2000ms, after which the next trial began. Participants performed a total of 144 trials, which were administered in three blocks, one block for each condition (low perceptual load, high perceptual load, degraded low load). Thus, in each condition, a total of 48 trials were presented and presentation of both the visual target letter ('X' or 'N') and auditory stimulus (auditory tone + noise or noise-only) was randomized. The block-order was also randomized and counterbalanced across participants. Prior to testing, participants completed a set of 12 practice trials (4 trials per condition). For the letter search task, reaction time (RT) and discrimination accuracy was recorded, whereas for the auditory detection task accuracy was recorded.

-- Figure 2 about here --

## **Results**

### *Visual search task*

Trials with RTs above 2500ms were discarded prior to analysis. A mixed Analysis of Variance (ANOVA) with group (ASD vs. NT) as a between-subjects factor and condition (low perceptual load, high perceptual load, and degraded low perceptual load) as a within-subjects factor was performed on RT data and error rates. There was a significant main effect of condition on RTs,  $F(2, 56) = 48.794, p < .001, \eta_p^2 = .635$  (see Supplementary Table 1 for task performance statistics). Follow-up contrasts revealed that RTs were significantly longer for high perceptual load displays ( $M = 1388, SD = 307.1$ ) than for degraded low load displays ( $M = 1170.6, SD = 337.1, t(29) = 4.614, p < .001, d = .67$ , see Figure 3), which in turn had longer RTs than low perceptual load displays ( $M = 961.3, SD = 282.9, t(29) = 4.931, p < .001, d = .67$ ). Significantly longer RTs were also observed in the high perceptual load condition compared to the low perceptual load condition ( $t(29) = 11.423, p < .001, d = 1.44$ ). There was no significant effect of group ( $F(1, 28) = 3.182, p = .085, \eta_p^2 = .102$ ) and no significant interaction between group and condition ( $F(2, 56) = .229, p = .796, \eta_p^2 = .008$ ) on RTs.

-- Figure 3 about here --

Error rates followed a similar pattern. Significant differences were observed across conditions ( $F(2, 56) = 25.644, p < .001, \eta_p^2 = .478$ ), with individual contrasts revealing significantly higher error rates in the high perceptual load condition ( $M = 0.28, SD = 0.14$ ) compared to both the degraded low load condition ( $M = 0.14, SD = 0.13, t(29) = 3.952, p < .001, d = 1.03$ ), and low perceptual load condition ( $M = 0.07, SD = 0.08, t(29) = 7.148, p < .001, d = 1.84$ ). Error rates in the low perceptual load condition were also significantly lower than in the degraded low load condition ( $t(29) = 3.138, p = .004, d = 0.65$ ). There was no main effect of group on error rates ( $F(1, 28) = .362, p = .552, \eta_p^2 = .013$ ) or interaction effect ( $F(2, 56) = .240, p = .788, \eta_p^2 = .008$ ). The findings therefore suggest that both target-stimulus degradation and increase in perceptual load resulted in an increase in general task difficulty as

indexed by longer RTs and reduced accuracy on the central letter task compared to a condition of low perceptual load with intact letter targets.

*Contrasting the effect of target-stimulus degradation and perceptual load on auditory detection*

The percentage detection rate, detection sensitivity ( $d'$ ) of the auditory stimulus and the response bias ( $c$ ) for each group was calculated separately for low load, degraded low load and high load conditions (see Supplementary Table 2). For detection rates, a repeated measures ANOVA indicated that there was a significant main effect of condition ( $F(2, 56) = 7.385, p = .001, \eta_p^2 = .209$ ), with follow-up contrasts showing that detection rates were significantly reduced in the high perceptual load condition ( $M = 0.76, SD = 0.2$ ) relative to the degraded low load condition ( $M = 0.84, SD = 0.16, t(29) = 2.258, p = .032, d = .40$ ), and low perceptual load condition ( $M = 0.89, SD = 0.1, t(29) = 3.353, p = .002, d = .78$ ). The difference in detection rates between the degraded low load and low perceptual load condition approached significance ( $t(29) = 2.032, p = .051, d = .37$ ), with a trend towards lower detection rates in the degraded low load condition (difference of approximately 5% in detection rates). Neither the main effect of group ( $F(1, 28) = .272, p = .606, \eta_p^2 = .01$ ), nor the interaction between group and condition was significant ( $F(2, 56) = 1.080, p = .347, \eta_p^2 = .037$ ).

The  $d'$  measure, an index of sensitivity or discrimination of a stimulus independent of a participant's response bias providing a more accurate reflection of task performance, was calculated for each individual and for each condition. There was a significant main effect of condition ( $F(2, 56) = 10.554, p < .001, \eta_p^2 = .274$ , see Figure 4), but no significant effect of group ( $F(1, 28) = .061, p = .807, \eta_p^2 = .002$ ) or interaction between group and condition ( $F(2, 56) = .037, p = .964, \eta_p^2 = .001$ ). Exploring the significant main effect of condition, it was revealed that detection sensitivity was significantly reduced in the high perceptual load

condition ( $d'$ :  $M = 1.89$ ,  $SD = 1.14$ ) relative to the degraded low load condition ( $d'$ :  $M = 2.57$ ,  $SD = 1.05$ ,  $t(29) = 3.677$ ,  $p = .001$ ,  $d = .62$ ), and low perceptual load condition ( $d'$ :  $M = 2.73$ ,  $SD = .76$ ,  $t(29) = 3.923$ ,  $p < .001$ ,  $d = .87$ ). Importantly, there was no significant difference in detection sensitivity between low perceptual load and degraded low load conditions ( $t(29) = .949$ ,  $p = .350$ ,  $d = .17$ ). This suggests that while an increase in perceptual load reduced perceptual sensitivity of the auditory stimulus, increasing task difficulty via target-stimulus degradation had no effect on detection sensitivity.

-- Figure 4 about here --

The response bias (i.e. response criterion:  $c$ ) was calculated for each participant, where a response criterion with a value greater than 0 indicates a bias towards the no response, a value of less than 0 indicates a bias towards the yes response and the value of 0 indicates no bias towards a yes or no response. Using ANOVA, the results showed that the response bias differed significantly between conditions ( $F(2, 56) = 3.445$ ,  $p = .039$ ,  $\eta_p^2 = .110$ ). There was no significant effect of group ( $F(1, 28) = .089$ ,  $p = .768$ ,  $\eta_p^2 = .003$ ), and no significant interaction effect ( $F(2, 56) = .178$ ,  $p = .837$ ,  $\eta_p^2 = .006$ ). Individual contrasts showed that the response bias was significantly increased (i.e. participants had a greater tendency to respond ‘stimulus absent’) in the degraded low load condition ( $M = 2.26$ ,  $SD = 2.01$ ) compared to the high perceptual load condition ( $M = 1.43$ ,  $SD = 1.08$ ,  $t(29) = 2.414$ ,  $p = .022$ ,  $d = .51$ ), and compared to the low perceptual load condition ( $M = 1.45$ ,  $SD = 1.24$ ), although this difference only approached significance ( $t(29) = 1.983$ ,  $p = .05$ ,  $d = .49$ ). There was no significant difference in response bias between low-and high perceptual load displays ( $t(29) = .065$ ,  $p = .948$ ,  $d = .02$ ).

#### *Analysis of relative speed between conditions*

It is important to acknowledge that the high perceptual load condition showed a greater task difficulty effect compared to the degraded low load condition as reflected by significantly



longer RTs and higher error rates. This might suggest that it is still higher task difficulty (as indexed by slower processing speed) that is driving the difference in detection sensitivity between these conditions. To further examine whether the relative speed difference between these conditions can account for the results on detection sensitivity, we re-analyzed the results for detection sensitivity by factoring in the relative overall speed in these conditions. Participants were divided into two groups using a median split procedure (Total sample: *Median* RT = 220ms, *Mean* RT = 218ms, range of RT = [-311;731]; see Supplementary Figure 1 for RT distribution) of the RT difference score between the high perceptual load and degraded low load condition. Participants with and without ASD were evenly distributed across these two groups (Group A:  $N_{ASD} = 7$ ;  $N_{TD} = 8$ ; Group B:  $N_{ASD} = 7$ ;  $N_{TD} = 8$ ). Group A was characterized by individuals with similar or reduced RTs in the degraded low load compared to the high load condition (*Median* RT = 74ms, *Mean* RT = 23ms, range of RT = [-311;218]), whereas group B was composed of individuals who were much slower in the high load relative to the degraded low load condition (*Median* RT = 419ms, *Mean* RT = 414ms, range of RT = [419;732]). If the difference in processing speed (i.e. effect of task difficulty) between the high perceptual load and degraded low load condition can account for the results on detection sensitivity, then we would expect a significant interaction between group (Group A, Group B) and condition (low load, high load, degraded low load). In other words, Group B (high speed difference) should show a difference in detection sensitivity between the degraded low load and high perceptual load condition, whereas Group A (no speed difference) should demonstrate no difference in detection sensitivity between these conditions.

This was however not the case, with an ANOVA showing no significant interaction effect of condition (low load, high load, degraded low load) and group (group A vs. group B) on detection sensitivity ( $F(2, 56) = 1.219$ ,  $p = .303$ ,  $\eta_p^2 = .042$ ). The association between RT difference scores and detection sensitivity across conditions was also assessed. For the low

load condition, there was a small positive, but non-significant association between RT difference scores and detection sensitivity ( $r = .21, p = .26$ ). Associations between RT difference scores and detection sensitivity were approaching zero in the high load ( $r = -.09, p = .62$ ) and degraded low load condition ( $r = -.02, p = .92$ ). Recall that the above analysis showed that while detection sensitivity was significantly reduced in the high perceptual load condition compared to low perceptual load and degraded low load condition, degraded low load did not result in a significant reduction in detection sensitivity compared to the low perceptual load condition. This analysis therefore rules out an alternative explanation of the differential effect of perceptual load compared to sensory degradation on detection sensitivity in terms of relative processing speed between these conditions.

### **Discussion**

This study contrasted the effects of visual perceptual load and task difficulty (via target stimulus degradation) on auditory detection sensitivity in individuals with ASD and neurotypical controls. The results indicated that the extent to which auditory detection sensitivity was modulated depended upon the type of processing demand imposed on participants by the relevant task. Increasing the visual perceptual load of the task by varying the relevant search set size resulted in a reduction in detection sensitivity (i.e. tapping into data “resource limits”; Lavie 2010; Remington et al. 2012; Tillmann and Swettenham 2017). In contrast, increasing general task difficulty by altering the sensory quality of the target stimulus by reducing its size and contrast did not reduce detection sensitivity (i.e. altering sensory “data limits”). This suggests a dissociation between increases in perceptual load and increases in general task difficulty in their effect on selective attention. Although both manipulations resulted in longer RTs and higher error rates compared to a low perceptual load condition with an intact target stimulus, only an increase in perceptual load modulated detection sensitivity.

Task difficulty in turn disrupted task performance while having no effect on auditory processing. The reduction in auditory detection sensitivity found at high levels of perceptual load therefore cannot simply be attributed to a general increase in task difficulty (as indexed by prolonged RTs and higher error rates on the primary task), but rather is specific to the attentional demands of the task. It was also shown that when controlling for relative speed difference between these conditions, the differential effect of perceptual load on detection sensitivity compared to sensory degradation still remained. This provides further evidence for the robustness of our findings.

Importantly, the pattern of findings was shown to be equivalent across diagnostic groups, suggesting that the extent to which participants could attend to an additional stimulus critically depended upon the level of perceptual load in the relevant task and available attentional resources rather than differences in more general task difficulty. This has important implications for the increased perceptual capacity account of ASD and studies supporting this theory. In these studies, enhanced processing of extraneous information in high perceptual load conditions in individuals with ASD was taken as evidence of increased perceptual capacity in ASD (Bayliss and Kritikos 2011; Ohta et al. 2012; Swettenham et al. 2014; Tillmann et al. 2015; Tillmann and Swettenham 2017; Remington et al. 2009; Remington et al. 2012). Yet, in order to make the claim that individuals with ASD have increased perceptual capacity, one needs to demonstrate that the differential effects of perceptual load in ASD indeed reflect an attention-specific mechanism that relates to a spill-over of spare attentional resources into the processing of extraneous information and not reflect effects of general task difficulty. Since none of these previous studies have disentangled the effects of perceptual load and task difficulty on attention, the current study makes important novel contributions to understanding and interpreting perceptual load effects in individuals with ASD. Specifically, the current study clarifies the role of perceptual load in selective attention in ASD by distinguishing it from

general effects of task difficulty and suggest that capacity limits play an important role in determining selective attention in ASD.

Note that the current study neither had the objective nor employed the necessary experimental design to test the increased perceptual capacity account in ASD. Evidence for increased capacity in individuals with ASD stems from the observation that individuals with ASD require higher levels of perceptual load to restore perceptual load effects on attention. For example, studies using a variation of the Eriksen response-competition task (Eriksen and Eriksen 1974) have shown that individuals with ASD continue to process distractors at higher levels of load (i.e. four items in array). At the highest level of perceptual load (i.e. six items in the array), load effects on distractor processing are restored and distractor processing is reduced to equivalent levels of NT controls (Remington et al. 2009; Tillmann and Swettenham 2017). Since in the current study we presented participants with the highest level of perceptual load (i.e. six items in the search array), we did not expect to find group differences in detection sensitivity.

Our results replicate, but also importantly extend, previous demonstrations of load-specific effects on attention in neurotypical individuals (Lavie and de Fockert 2003; Yeshurun and Marciano 2013). In these studies, the effects of visual perceptual load relative to target stimulus degradation on distractor processing were assessed via response interference effects. That is, the extent to which a distractor was processed was reflected in the RT costs associated with the presence of a response-incongruent distractor (requiring the opposite target response). The absence of RT differences between incompatible compared to neutral or compatible trials was taken as evidence that distractors were not processed. Although these studies demonstrated that distractor processing is reduced or even eliminated in conditions of high perceptual load, but not in conditions of low perceptual load with a degraded target stimulus, this paradigm only provides an indirect measure of distractor perception (via RT interference effects). In contrast,

the current study assessed perceptual sensitivity of an extraneous stimulus using a dual-task paradigm, in line with previous work in NT adults (Macdonald and Lavie 2008; Raveh and Lavie 2015) and individuals with ASD (Remington et al. 2012; Tillmann and Swettenham 2017). Measuring perceptual sensitivity (e.g.  $d'$ ) has the advantage that its value does not depend upon the response criterion the subject is adopting, thereby providing a true measure of a subject's perceptual sensitivity. This establishes a complimentary and more robust account of the differential effects of load and stimulus degradation on selective attention.

Several limitations of the current study however remain, notably the small size of the sample tested, and restricted age and IQ range studied, which somewhat limit the conclusions drawn from the study. For example, we were unable to address how developmental (i.e. age-related changes) and cognitive factors (i.e. IQ) interact differently with task performance. While this would be important to address in future studies, the complex and demanding task design in the current study did not allow us to pursue these research questions in more detail. Notwithstanding these limitations, the primary focus of this study was to provide a critical test of one of the central assumptions of the perceptual capacity account in ASD. The present results clarify the role of perceptual load in selective attention in ASD by distinguishing it from the general effects of task difficulty and propose that capacity limits play a critical role in selective attention in ASD.

**Ethical approval:** All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

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**Table 1** Descriptive statistics for each group

<b>Group</b>	<b>Statistic</b>	<b>CA range</b> (years : months)	<b>Raven's Score</b>	<b>SCQ score</b>
<b>ASD</b> ( <i>n</i> = 14)	<i>M</i>	14:8	45.4	25.3
	<i>SD</i>	1:7	6.1	5.4
	Range	12:6 – 17:5	37 – 56	18 - 35
<b>TD</b> ( <i>n</i> = 16)	<i>M</i>	14:8	48.6	
	<i>SD</i>	0:6	5.6	
	Range	13:8 – 15:4	33 – 56	

Note: ASD = Autism Spectrum Disorder, CA = Chronological Age, SCQ = Social Communication Questionnaire, TD = Typically Developing